US011042025B2

(12) **United States Patent**
Uyeno et al.

(10) **Patent No.: US 11,042,025 B2**
(45) **Date of Patent: Jun. 22, 2021**

(54) **OPTICAL DATA COMMUNICATION USING MICRO-ELECTRO-MECHANICAL SYSTEM (MEMS) MICRO-MIRROR ARRAYS**

(71) Applicant: **Raytheon Company**, Waltham, MA (US)

(72) Inventors: **Gerald P. Uyeno**, Tucson, AZ (US); **Sean D. Keller**, Tucson, AZ (US); **Benn H. Gleason**, Tucson, AZ (US)

(73) Assignee: **Raytheon Company**, Waltham, MA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **16/871,602**

(22) Filed: **May 11, 2020**

(65) **Prior Publication Data**

US 2021/0088776 A1 Mar. 25, 2021

Related U.S. Application Data

(60) Provisional application No. 62/903,244, filed on Sep. 20, 2019.

(51) **Int. Cl.**
G02B 26/08 (2006.01)
H04J 14/02 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***G02B 26/0841*** (2013.01); ***G02B 6/3512*** (2013.01); ***H04J 14/0267*** (2013.01); ***H04Q 11/0005*** (2013.01)

(58) **Field of Classification Search**
CPC G02B 26/0841; G02B 6/3512; H04J 14/0267; H04Q 11/0005
(Continued)

(56) **References Cited**

U.S. PATENT DOCUMENTS

6,567,574 B1 * 5/2003 Ma H04Q 11/0005 385/16
7,660,235 B2 * 2/2010 Alicherry H04L 45/28 370/217
(Continued)

OTHER PUBLICATIONS

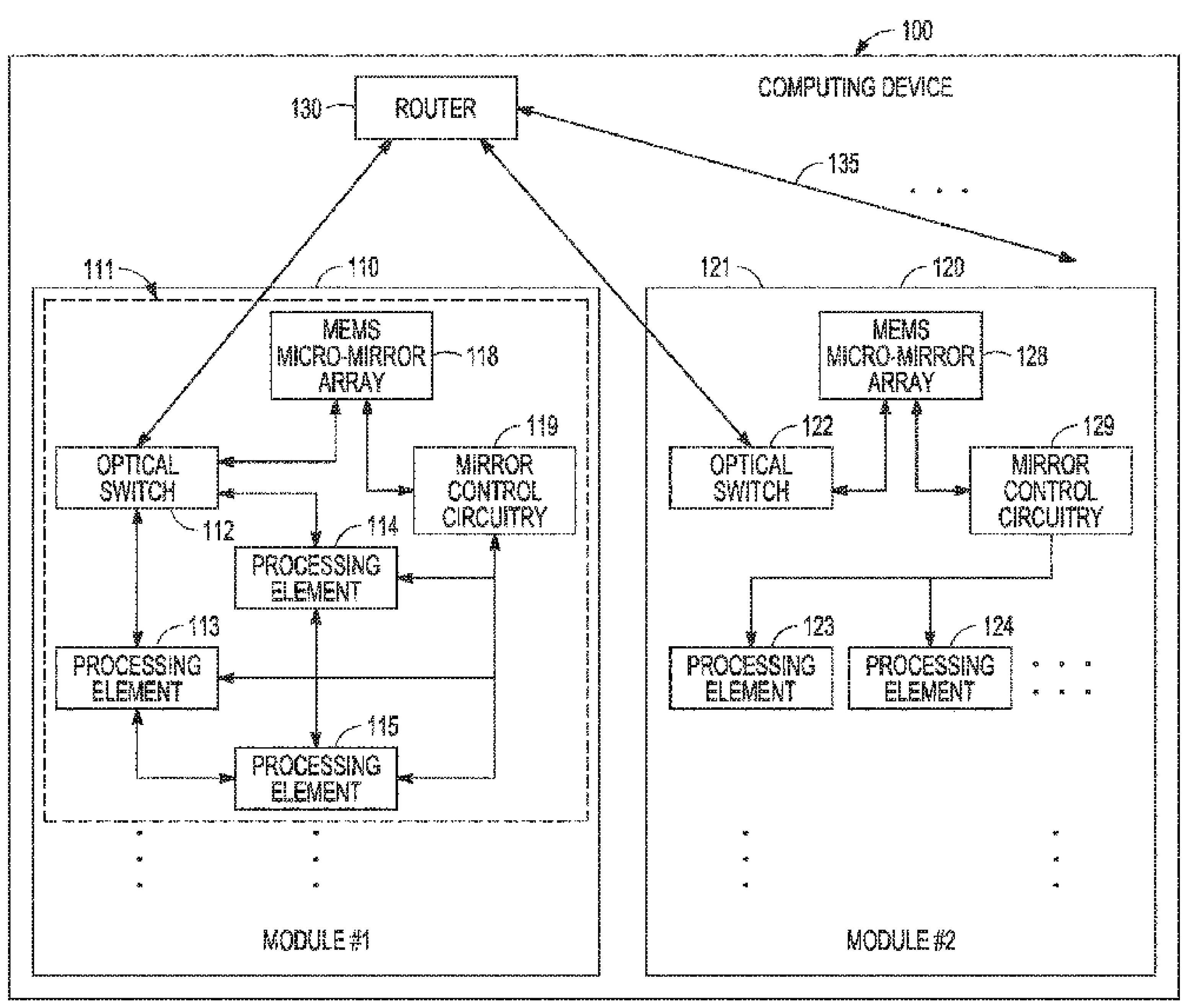
"Mirrorcle Technologies MEMS Mirrors—Technical Overview", Mirrorcle Technologies, Inc., (2018), 7 pgs.

Primary Examiner — Dalzid E Singh
(74) *Attorney, Agent, or Firm* — Schwegman Lundberg & Woessner, P.A.

(57) **ABSTRACT**

Embodiments of an optical data communication apparatus using micro-electro-mechanical system (MEMS) micro-mirror arrays is described herein. The apparatus may include a router configured to operate as a relay to exchange optical data signals between optical switches of the apparatus. The optical switches may be configured to switch between reflection directions to reflect the optical signals over different optical connections between the optical switches and different receiving ports of the router. The reflection directions may be switched in accordance with predetermined mappings between the receiving ports of the router and destinations of the optical signals. The router includes a MEMS micro-mirror array configured to reflect received optical signals to the destinations. A processing element of the optical data switching circuitry may generate a plurality of optical data signals and may send the optical data signals to an optical switch of the optical data switching circuitry.

28 Claims, 7 Drawing Sheets



(51) **Int. Cl.**
H04Q 11/00 (2006.01)
G02B 6/35 (2006.01)

(58) **Field of Classification Search**
USPC 398/48
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

8,983,293	B2*	3/2015	Frankel	G02B 6/26 398/50
9,473,768	B2	10/2016	Uyeno et al.	
10,243,654	B1	3/2019	Uyeno et al.	
10,444,492	B2	10/2019	Hopkins et al.	
2002/0141689	A1*	10/2002	Qian	G02B 6/3588 385/18
2003/0081321	A1*	5/2003	Moon	G02B 6/2931 359/619
2003/0185488	A1*	10/2003	Blumenthal	H04Q 11/0005 385/16
2005/0031255	A1*	2/2005	Schroeder	G02B 6/359 385/18
2007/0036480	A1*	2/2007	Wu	G02B 6/3556 385/16
2008/0050064	A1*	2/2008	Sakai	H04Q 11/0005 385/17
2012/0155885	A1*	6/2012	Hannah	H04B 10/1143 398/128
2015/0172218	A1*	6/2015	Beshai	H04J 14/0267 370/401
2017/0293137	A1*	10/2017	Zhao	G02B 26/08
2018/0231715	A1*	8/2018	Bishop	G02B 26/02
2019/0154921	A1*	5/2019	Xing	G02B 6/3502

* cited by examiner

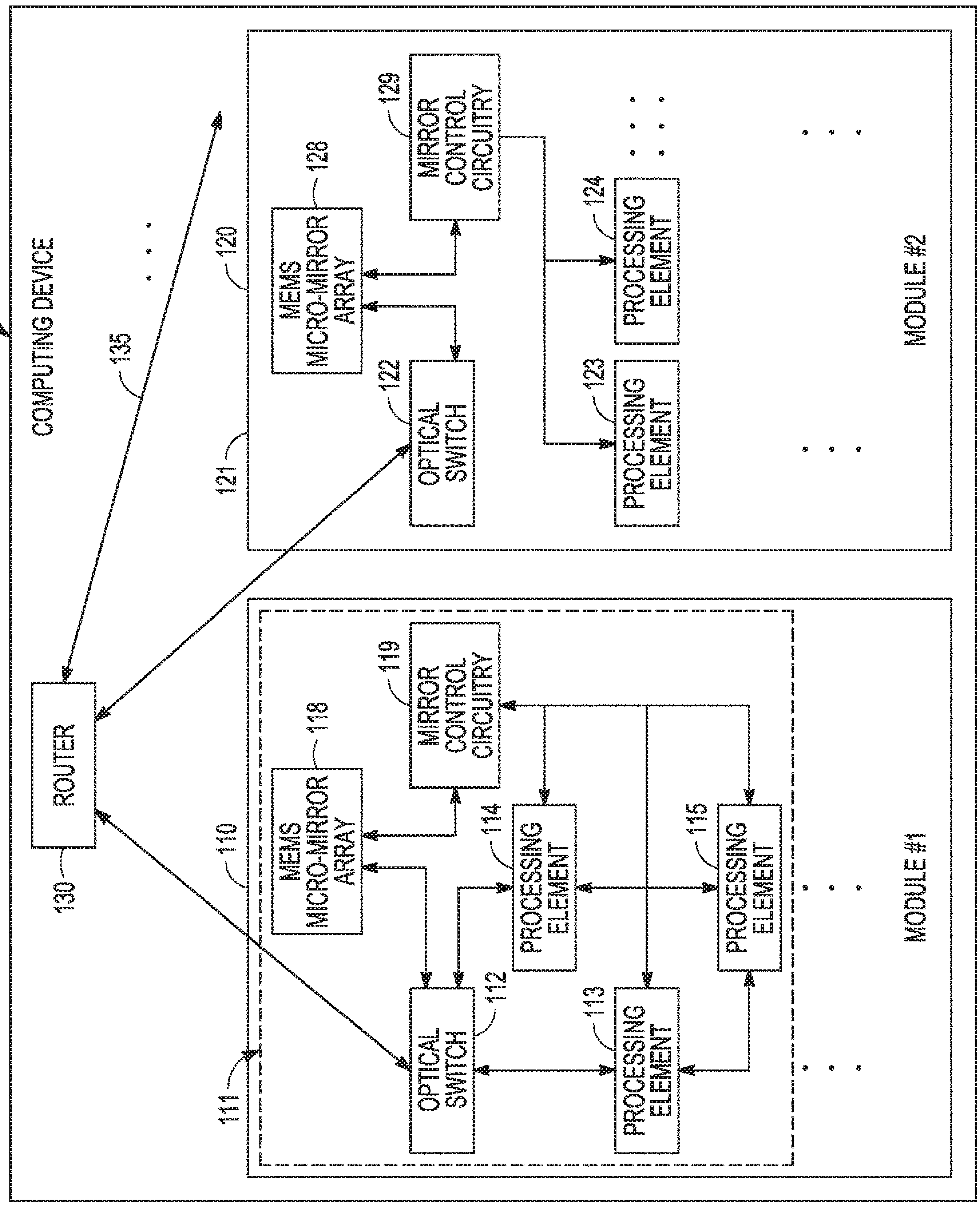

100
COMPUTING DEVICE
135
ROUTER
130
110
111
MEMS MICRO-MIRROR ARRAY
118
MIRROR CONTROL CIRCUITRY
119
OPTICAL SWITCH
112
PROCESSING ELEMENT
113
PROCESSING ELEMENT
114
PROCESSING ELEMENT
115
MODULE #1
120
121
MEMS MICRO-MIRROR ARRAY
128
MIRROR CONTROL CIRCUITRY
129
OPTICAL SWITCH
122
PROCESSING ELEMENT
123
PROCESSING ELEMENT
124
MODULE #2

FIG. 1

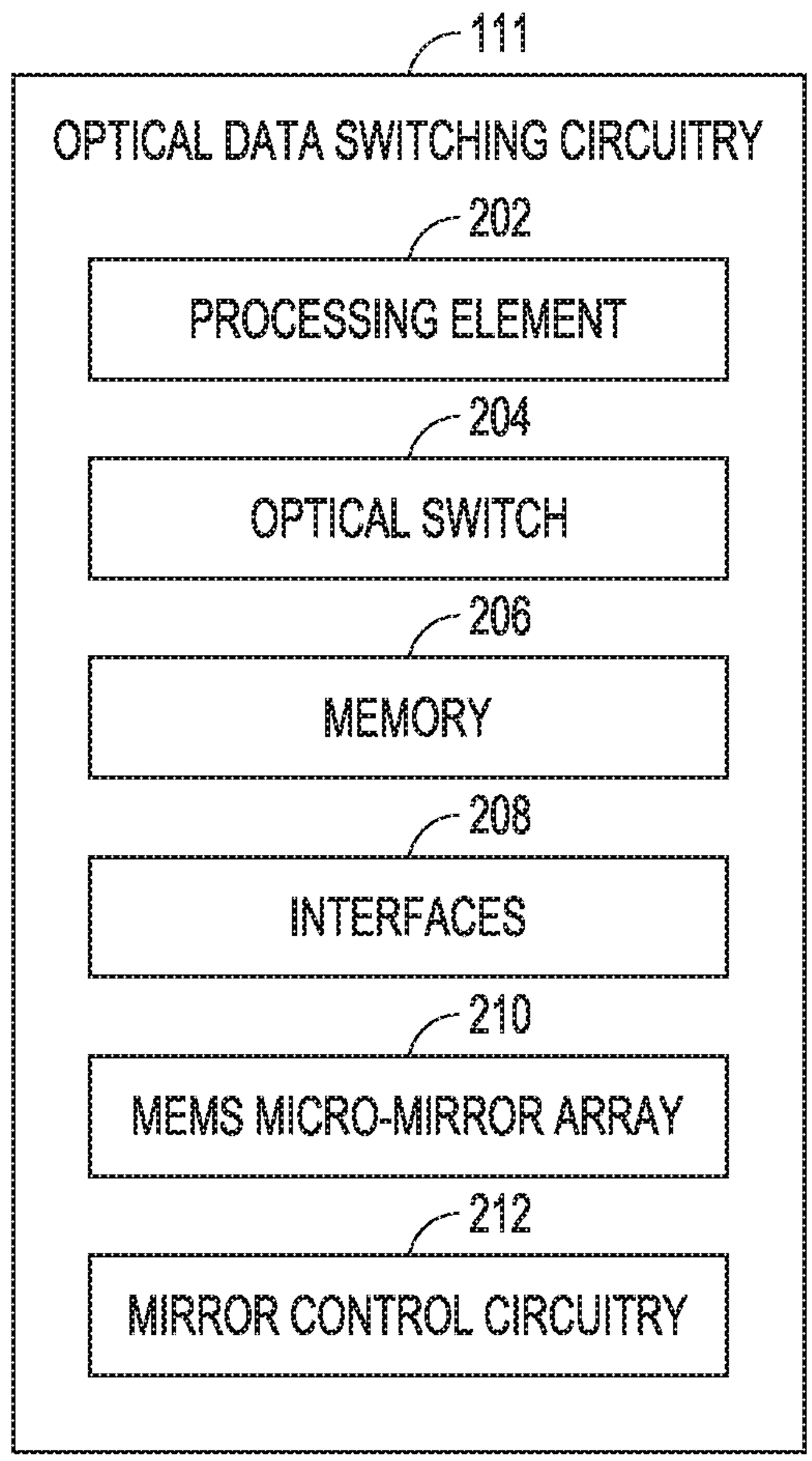

111
OPTICAL DATA SWITCHING CIRCUITRY
202
PROCESSING ELEMENT
204
OPTICAL SWITCH
206
MEMORY
208
INTERFACES
210
MEMS MICRO-MIRROR ARRAY
212
MIRROR CONTROL CIRCUITRY

FIG. 2

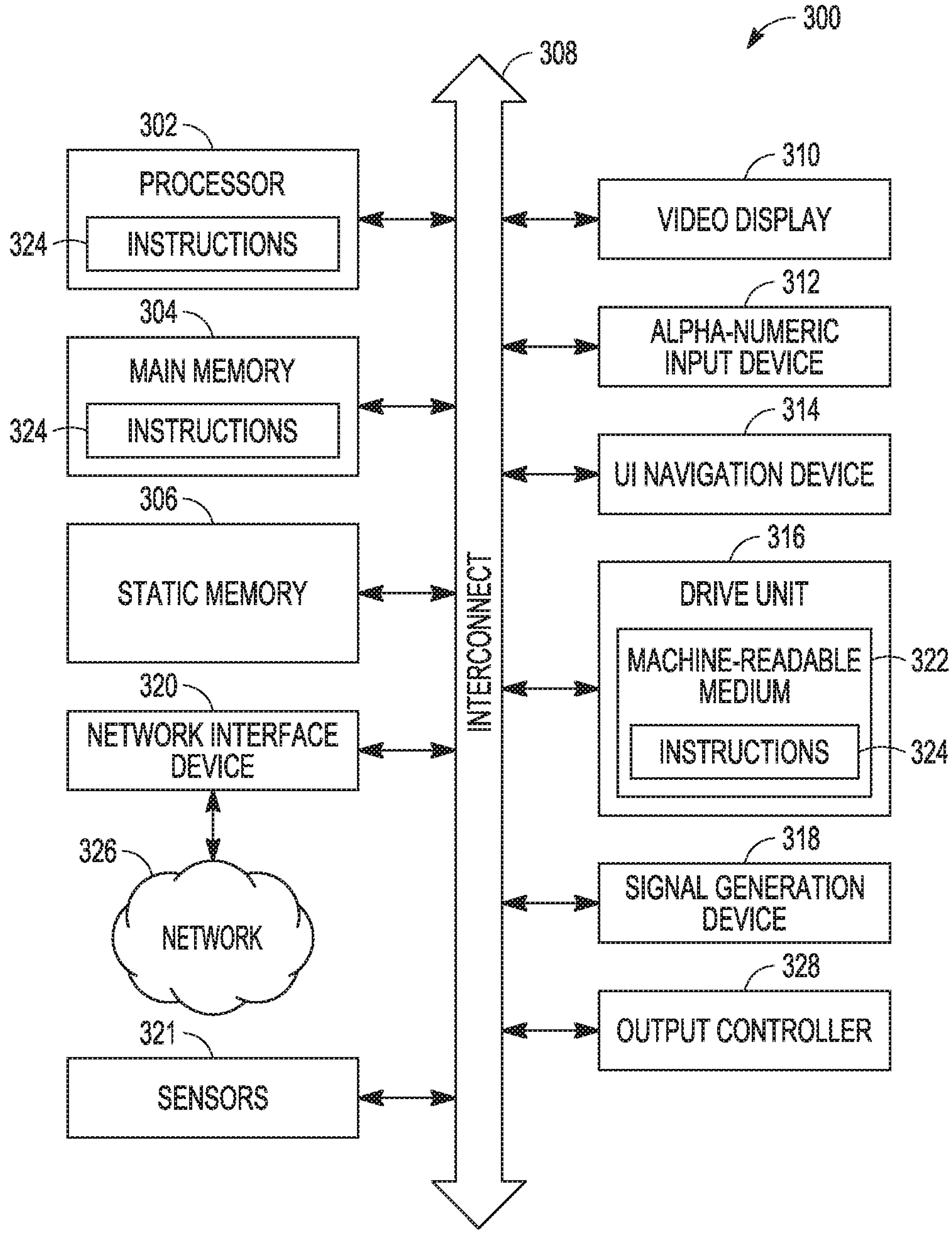

300
308
302
PROCESSOR
324
INSTRUCTIONS
304
MAIN MEMORY
324
INSTRUCTIONS
306
STATIC MEMORY
320
NETWORK INTERFACE DEVICE
326
NETWORK
321
SENSORS
INTERCONNECT
310
VIDEO DISPLAY
312
ALPHA-NUMERIC INPUT DEVICE
314
UI NAVIGATION DEVICE
316
DRIVE UNIT
MACHINE-READABLE MEDIUM
322
INSTRUCTIONS
324
318
SIGNAL GENERATION DEVICE
328
OUTPUT CONTROLLER

FIG. 3

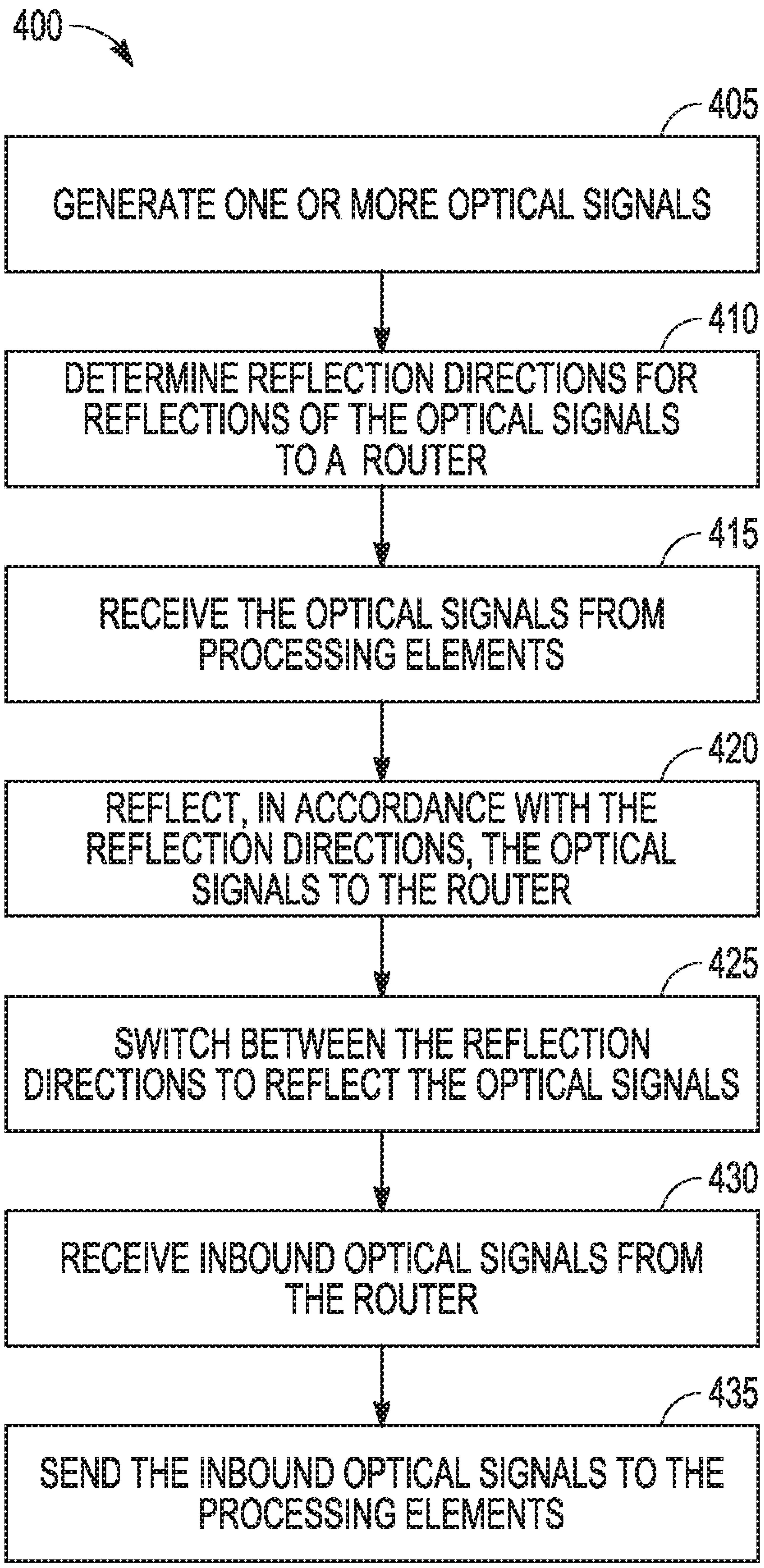

400
405
GENERATE ONE OR MORE OPTICAL SIGNALS
410
DETERMINE REFLECTION DIRECTIONS FOR REFLECTIONS OF THE OPTICAL SIGNALS TO A ROUTER
415
RECEIVE THE OPTICAL SIGNALS FROM PROCESSING ELEMENTS
420
REFLECT, IN ACCORDANCE WITH THE REFLECTION DIRECTIONS, THE OPTICAL SIGNALS TO THE ROUTER
425
SWITCH BETWEEN THE REFLECTION DIRECTIONS TO REFLECT THE OPTICAL SIGNALS
430
RECEIVE INBOUND OPTICAL SIGNALS FROM THE ROUTER
435
SEND THE INBOUND OPTICAL SIGNALS TO THE PROCESSING ELEMENTS

FIG. 4

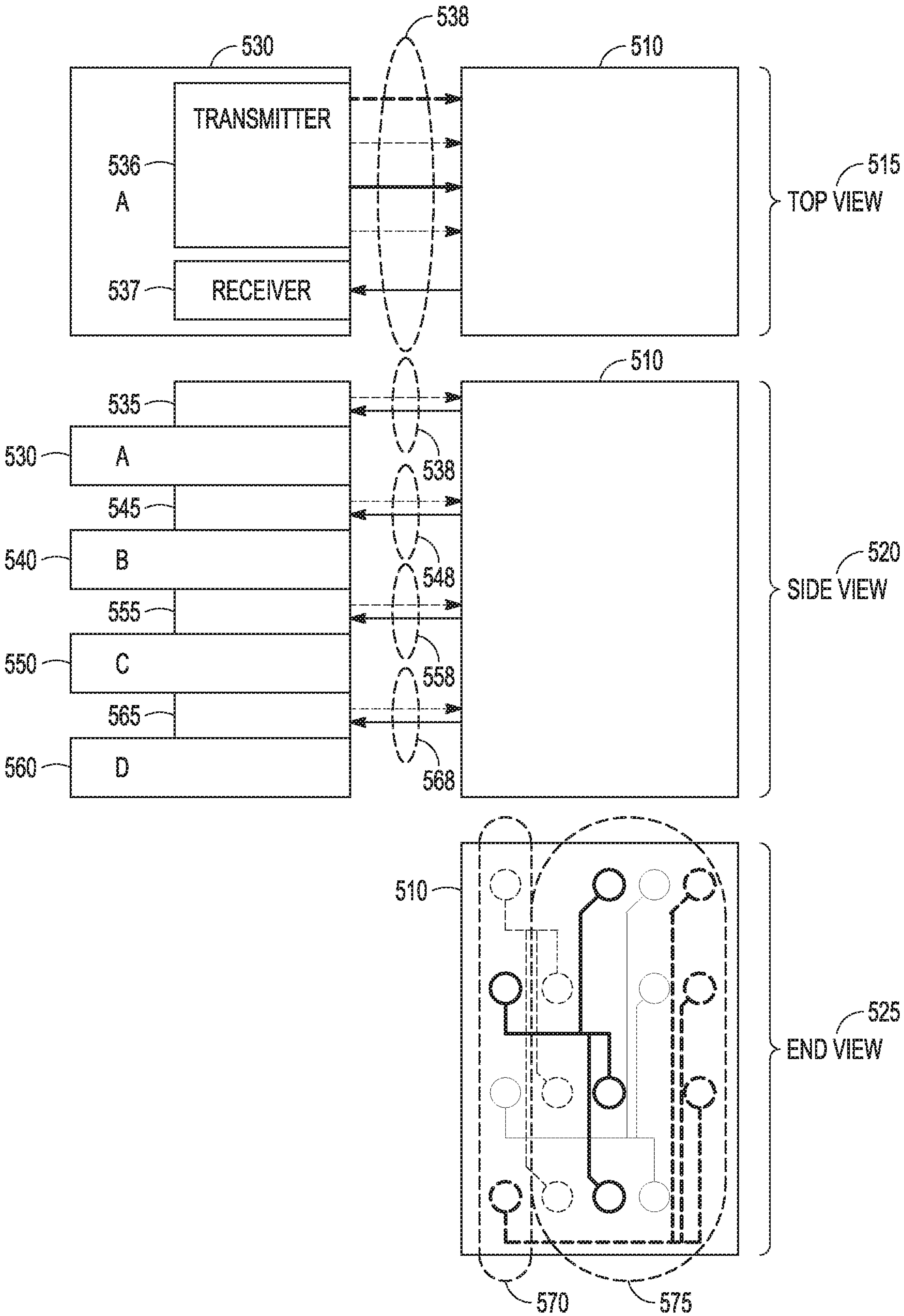

538
530
510
TRANSMITTER
536
A
515
TOP VIEW
537
RECEIVER
510
535
530
A
538
545
540
B
548
555
520
SIDE VIEW
550
C
558
565
560
D
568
510
525
END VIEW
570
575

FIG. 5

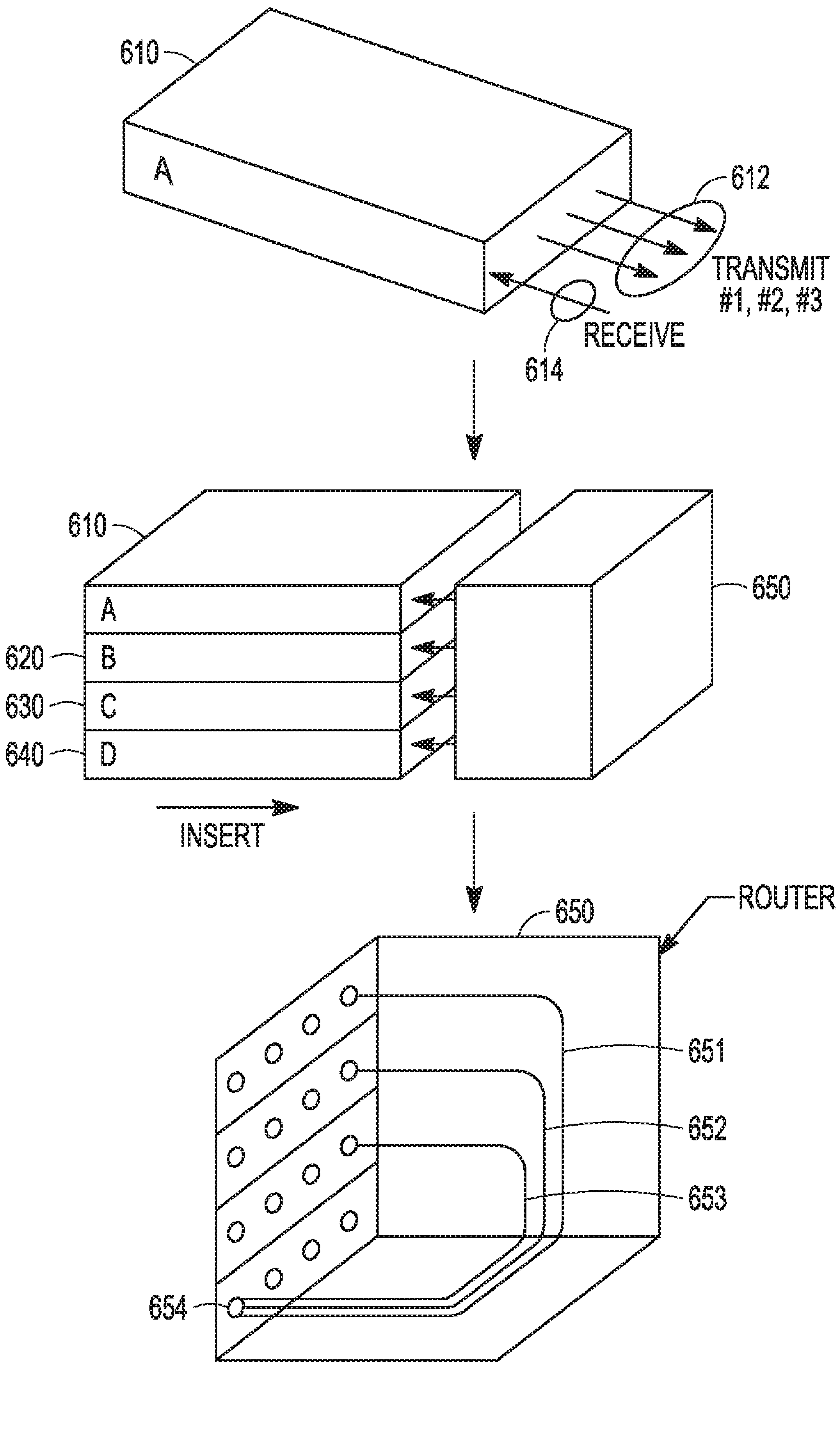

610
A
612
TRANSMIT
#1, #2, #3
RECEIVE
614
610
A
620
B
630
C
640
D
INSERT
650
650
ROUTER
651
652
653
654

FIG. 6

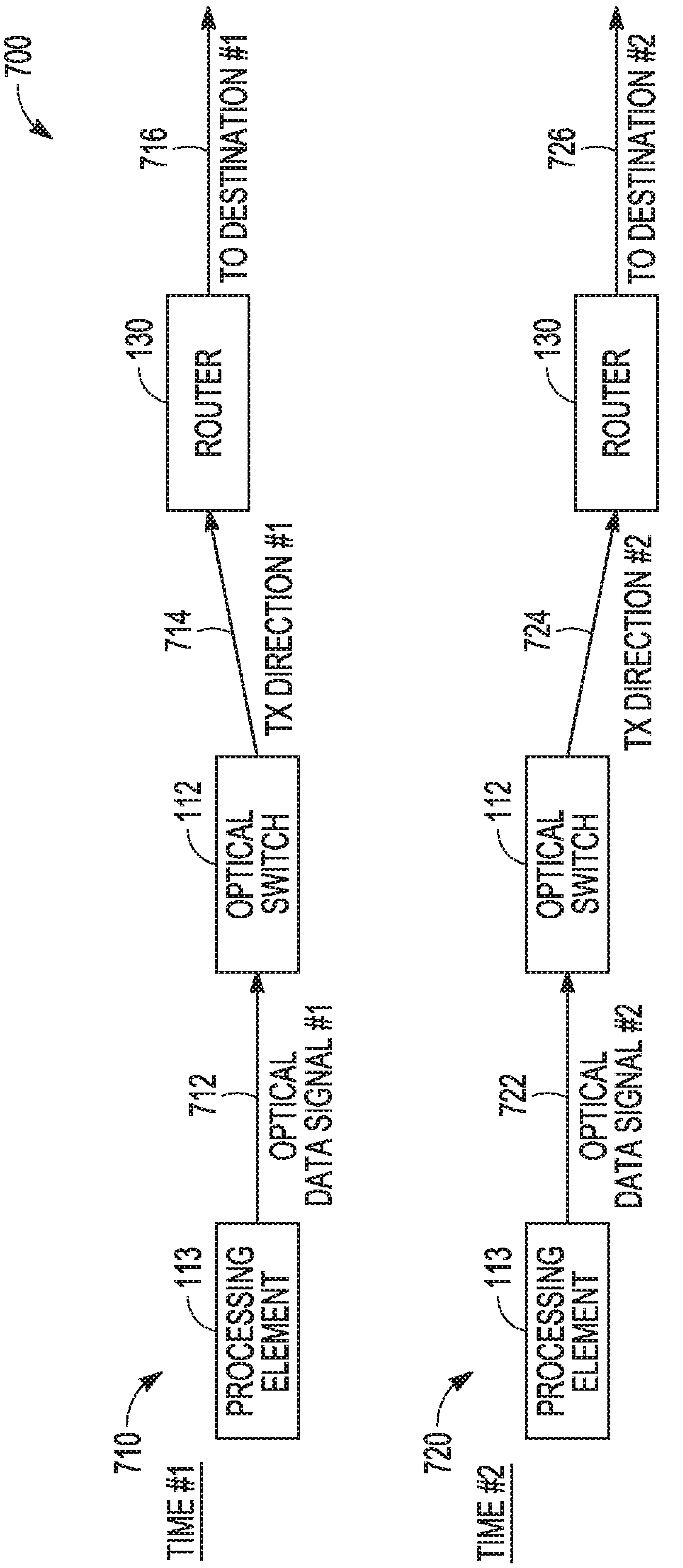

700
TIME #1
710
113
PROCESSING ELEMENT
712
OPTICAL DATA SIGNAL #1
112
OPTICAL SWITCH
714
TX DIRECTION #1
130
ROUTER
716
TO DESTINATION #1
TIME #2
720
113
PROCESSING ELEMENT
722
OPTICAL DATA SIGNAL #2
112
OPTICAL SWITCH
724
TX DIRECTION #2
130
ROUTER
726
TO DESTINATION #2

FIG. 7

OPTICAL DATA COMMUNICATION USING MICRO-ELECTRO-MECHANICAL SYSTEM (MEMS) MICRO-MIRROR ARRAYS

PRIORITY CLAIM

This application claims priority to U.S. Provisional Patent Application Ser. No. 62/903,244, filed Sep. 20, 2019 [reference number 19-13085-US-PSP] which is incorporated herein by reference in its entirety.

TECHNICAL FIELD

Embodiments pertain to optical data switching and data communications using Micro-Electro-Mechanical Systems (MEMS) micro-mirror arrays.

BACKGROUND

In some systems, processing elements may exchange signals with each other to communication results, outputs or other information. For instance, operations performed by a particular processing element of a system may be output to another processing element. In some cases, the other processing element may be at another physical location of the system, such as on a different processor board. Communication between elements in such scenarios may be challenging due to any number of factors. As an example, the number of processing elements in the system may be high or may increase and the number of required exchanges is even higher, increasing as the square of the number of processing elements. As another example, delays in communication of information between processing elements may affect system performance. Accordingly, there is a general need for systems and methods to enable rapid signal switching between large numbers of processing elements in these and other scenarios.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates an example of a computing device in accordance with some embodiments;

FIG. **2** illustrates an example of optical data switching circuitry in accordance with some embodiments;

FIG. **3** illustrates a block diagram of an example machine in accordance with some embodiments;

FIG. **4** illustrates the operation of a method of communication of optical signals in accordance with some embodiments;

FIG. **5** illustrates an example of optical connectivity between an optical switch and a router in accordance with some embodiments;

FIG. **6** illustrates another example of optical connectivity between an optical switch and a router in accordance with some embodiments; and

FIG. **7** illustrates example flows of optical signals in accordance with some embodiments.

DETAILED DESCRIPTION

The following description and the drawings sufficiently illustrate specific embodiments to enable those skilled in the art to practice them. Some embodiments may incorporate structural, logical, electrical, process, and other changes. Portions and features of some embodiments may be included in, or substituted for, those of other embodiments. Embodiments set forth in the claims encompass all available equivalents of those claims.

FIG. **1** illustrates an example of a computing device in accordance with some embodiments. It should be noted that embodiments are not limited to the example computing device **100** shown in FIG. **1**, in terms of number, type and/or arrangement of components. Some embodiments may not necessarily include all components shown in the example computing device **100**. Some embodiments may include additional components not shown in the example computing device **100**. In some embodiments, one or more components may be used in place of one or more components shown in the example computing device **100** and may provide same or similar functionality to components shown in the example computing device **100**.

The example computing device **100** may include any number of modules, such as the first module **110** and the second module **110**. It should be noted that embodiments are not limited to two modules **110**, **120**, as any suitable number of modules may be included in the computing device **100**. The first module **110** may include an optical switch **112** and one or more processing elements **113**-**115**, which may be connected through interface circuitry (such as **116**) which may include optical circuitry, waveguides, wires and/or a combination thereof. It should be noted that embodiments are not limited to the examples of connectivity shown between processing elements **113**-**115** or between the optical switch **112** and the processing elements **113**-**115**. The first module **110** may also include additional components. In accordance with some embodiments, the optical switch **112** may exchange optical signals with the router **130**. These embodiments will be described in more detail below.

The second module **120** may include an optical switch **122**, one or more processing elements (such as **123**, **124** and/or others) and/or other components. In some embodiments, the optical switch **122** may exchange optical signals with the router **130**, as will be described herein. The router **130** may also exchange optical signals with any suitable number of other modules and/or components, in some embodiments.

As used herein, the term "circuitry" may refer to, be part of, or include optical components, an optical circuit, an Application Specific Integrated Circuit (ASIC), an electronic circuit, a processor (shared, dedicated, or group), and/or memory (shared, dedicated, or group) that execute one or more software or firmware programs, a combinational logic circuit, and/or other suitable hardware components that provide the described functionality. In some embodiments, the circuitry may be implemented in, or functions associated with the circuitry may be implemented by, one or more software or firmware modules. In some embodiments, circuitry may include logic, at least partially operable in hardware. Embodiments described herein may be implemented into a system using any suitably configured hardware and/or software.

FIG. **2** illustrates an example of optical data switching circuitry in accordance with some embodiments. The optical data switching circuitry **111** may include one or more processing elements **202** and one or more optical switches **204**, in some embodiments. In some embodiments, optical data switching circuitry **111** may include one or more micro-electrical mechanical (MEMS) micro-mirror arrays **118** and mirror control circuitry **119**. In some embodiments, the optical switch **204** may include one or more MEMS micro-mirror arrays **118** and mirror control circuitry **119**. Referring to FIG. **1**, the optical switch **112** and the processing elements **113-115** may be included as part of the optical data switching circuitry **111** included in the first module **110**, in some cases. Similarly, the optical switch **122** and the processing elements **123** and **124** may be included as part of an optical data switching circuitry included in the second module **120**, in some cases. The optical data switching circuitry **111** may also include memory **206** in some embodiments, which may be used by the optical data switching circuitry **111** as part of the performance of some of the operations described herein. The optical data switching circuitry **111** may also include one or more interfaces **208** in some embodiments, which may enable communication between components of the optical data switching circuitry **111**. In some embodiments, the interfaces **208** may enable communication between one or more components of the optical data switching circuitry **111** and one or more external components. The interfaces **208** may include wired interfaces, optical interfaces, waveguides or a combination thereof, in some embodiments.

FIG. **3** illustrates a block diagram of an example machine in accordance with some embodiments. Any one or more of the techniques (e.g., methodologies) discussed herein may be performed on such a machine **300**, in some embodiments. In alternative embodiments, the machine **300** may operate as a standalone device or may be connected (e.g., networked) to other machines. In a networked deployment, the machine **300** may operate in the capacity of a server machine, a client machine, or both in server-client network environments. In an example, the machine **300** may act as a peer machine in peer-to-peer (P2P) (or other distributed) network environment. In some embodiments, the machine **300** may be a personal computer (PC), a tablet PC, a set-top box (STB), a personal digital assistant (PDA), a mobile device, a base station, an access point (AP) arranged to operate in accordance with an IEEE 802.11 protocol and/or a wireless local area network (WLAN) protocol, a station (STA) arranged to operate in accordance with an IEEE 802.11 protocol and/or a wireless local area network (WLAN) protocol, a User Equipment (UE) arranged to operate in accordance with a cellular or Third Generation Partnership Project (3GPP) protocol (including Long Term Evolution (LTE) protocols), an Evolved Node-B (eNB) arranged to operate in accordance with a 3GPP protocol (including LTE protocols), a mobile telephone, a smart phone, a web appliance, a network router, switch or bridge, or any machine capable of executing instructions (sequential or otherwise) that specify actions to be taken by that machine. Further, while only a single machine is illustrated, the term "machine" shall also be taken to include any collection of machines that individually or jointly execute a set (or multiple sets) of instructions to perform any one or more of the methodologies discussed herein, such as cloud computing, software as a service (SaaS), other computer cluster configurations.

Examples, as described herein, may include, or may operate on, logic or a number of components, modules, or mechanisms. Modules are tangible entities (e.g., hardware) capable of performing specified operations and may be configured or arranged in a certain manner. In an example, circuits may be arranged (e.g., internally or with respect to external entities such as other circuits) in a specified manner as a module. In an example, the whole or part of one or more computer systems (e.g., a standalone, client or server computer system) or one or more hardware processors may be configured by firmware or software (e.g., instructions, an application portion, or an application) as a module that operates to perform specified operations. In an example, the software may reside on a machine readable medium. In an example, the software, when executed by the underlying hardware of the module, causes the hardware to perform the specified operations.

Accordingly, the term "module" is understood to encompass a tangible entity, be that an entity that is physically constructed, specifically configured (e.g., hardwired), or temporarily (e.g., transitorily) configured (e.g., programmed) to operate in a specified manner or to perform part or all of any operation described herein. Considering examples in which modules are temporarily configured, each of the modules need not be instantiated at any one moment in time. For example, where the modules comprise a general-purpose hardware processor configured using software, the general-purpose hardware processor may be configured as respective different modules at different times. Software may accordingly configure a hardware processor, for example, to constitute a particular module at one instance of time and to constitute a different module at a different instance of time.

As a non-limiting example, a module may include a group of components connected to (permanently, temporarily and/or semi-permanently) a circuit board, processor board and/or other medium.

Machine (e.g., computer system) **300** may include a hardware processor **302** (e.g., a central processing unit (CPU), a graphics processing unit (GPU), a hardware processor core, or any combination thereof), a main memory **304** and a static memory **306**, some or all of which may communicate with each other via an interconnect (e.g., bus) **308**. In some embodiments, components of the machine **300** may communicate with each other via optical interfaces, waveguides and/or other circuitry configured to exchange optical signals. In some embodiments, the interconnect **308** may be configured to communicate optical signals and/or other signals between components of the machine **300**.

The machine **300** may further include a display unit **310**, an alphanumeric input device **312** (e.g., a keyboard), and a user interface (UI) navigation device **314** (e.g., a mouse). In an example, the display unit **310**, input device **312** and UI navigation device **314** may be a touch screen display. The machine **300** may additionally include a storage device (e.g., drive unit) **316**, a signal generation device **318** (e.g., a speaker), a network interface device **320**, and one or more sensors **321**, such as a global positioning system (GPS) sensor, compass, accelerometer, or other sensor. The machine **300** may include an output controller **328**, such as a serial (e.g., universal serial bus (USB), parallel, or other wired or wireless (e.g., infrared (IR), near field communication (NFC), etc.) connection to communicate or control one or more peripheral devices (e.g., a printer, card reader, etc.).

The storage device **316** may include a machine readable medium **322** on which is stored one or more sets of data structures or instructions **324** (e.g., software) embodying or utilized by any one or more of the techniques or functions described herein. The instructions **324** may also reside, completely or at least partially, within the main memory **304**, within static memory **306**, or within the hardware processor **302** during execution thereof by the machine **300**. In an example, one or any combination of the hardware processor **302**, the main memory **304**, the static memory **306**, or the storage device **316** may constitute machine readable media.

While the machine readable medium **322** is illustrated as a single medium, the term "machine readable medium" may include a single medium or multiple media (e.g., a centralized or distributed database, and/or associated caches and servers) configured to store the one or more instructions **324**.

The term "machine readable medium" may include any medium that is capable of storing, encoding, or carrying instructions for execution by the machine **300** and that cause the machine **300** to perform any one or more of the techniques of the present disclosure, or that is capable of storing, encoding or carrying data structures used by or associated with such instructions. Non-limiting machine-readable medium examples may include solid-state memories, and optical and magnetic media. Specific examples of machine readable media may include: non-volatile memory, such as semiconductor memory devices (e.g., Electrically Programmable Read-Only Memory (EPROM), Electrically Erasable Programmable Read-Only Memory (EEPROM)) and flash memory devices; magnetic disks, such as internal hard disks and removable disks; magneto-optical disks; Random Access Memory (RAM); and CD-ROM and DVD-ROM disks. In some examples, machine readable media may include non-transitory machine-readable media. In some examples, machine readable media may include machine readable media that is not a transitory propagating signal.

The instructions **324** may further be transmitted or received over a communications network **326** using a transmission medium via the network interface device **320** utilizing any one of a number of transfer protocols (e.g., frame relay, internet protocol (IP), transmission control protocol (TCP), user datagram protocol (UDP), hypertext transfer protocol (HTTP), etc.). Example communication networks may include a local area network (LAN), a wide area network (WAN), a packet data network (e.g., the Internet), mobile telephone networks (e.g., cellular networks), Plain Old Telephone (POTS) networks, and wireless data networks (e.g., Institute of Electrical and Electronics Engineers (IEEE) 802.11 family of standards known as Wi-Fi®, IEEE 802.16 family of standards known as WiMax®), IEEE 802.15.4 family of standards, a Long Term Evolution (LTE) family of standards, a Universal Mobile Telecommunications System (UMTS) family of standards, peer-to-peer (P2P) networks, among others. In an example, the network interface device **320** may include one or more physical jacks (e.g., Ethernet, coaxial, or phone jacks) or one or more antennas to connect to the communications network **326**. In an example, the network interface device **320** may include a plurality of antennas to wirelessly communicate using at least one of single-input multiple-output (SIMO), multiple-input multiple-output (MIMO), or multiple-input single-output (MISO) techniques. In some examples, the network interface device **320** may wirelessly communicate using Multiple User MIMO techniques. The term "transmission medium" shall be taken to include any intangible medium that is capable of storing, encoding or carrying instructions for execution by the machine **300**, and includes digital or analog communications signals or other intangible medium to facilitate communication of such software

It should be noted that in some embodiments, optical data switching circuitry may include some or all of the components shown in either FIG. **2** or FIG. **3** or both. It should also be noted that in some embodiments, a computing device may include some or all of the components shown in either FIG. **1** or FIG. **3** or both. In some embodiments, a device (such as the example devices described above and/or others) may include one or more components shown in FIG. **1** and/or FIG. **2** and/or FIG. **3**. For instance, in some embodiments, a mobile device may include some components of FIG. **3** and some components of the optical data switching circuitry **111**, which may be arranged in a manner similar to the arrangement shown in FIG. **1**.

Although the computing device **100**, the optical data switching circuitry **111**, and the machine **300** are illustrated as having several separate functional elements, one or more of the functional elements may be combined and may be implemented by combinations of software-configured elements, such as processing elements including digital signal processors (DSPs), and/or other hardware elements. For example, some elements may comprise one or more microprocessors, DSPs, field-programmable gate arrays (FPGAs), application specific integrated circuits (ASICs), radio-frequency integrated circuits (RFICs) and combinations of various hardware and logic circuitry for performing at least the functions described herein. In some embodiments, the functional elements may refer to one or more processes operating on one or more processing elements. Embodiments may be implemented in one or a combination of hardware, firmware and software. Embodiments may also be implemented as instructions stored on a computer-readable storage device, which may be read and executed by at least one processor to perform the operations described herein. A computer-readable storage device may include any non-transitory mechanism for storing information in a form readable by a machine (e.g., a computer). For example, a computer-readable storage device may include read-only memory (ROM), random-access memory (RAM), magnetic disk storage media, optical storage media, flash-memory devices, and other storage devices and media. Some embodiments may include one or more processors and may be configured with instructions stored on a computer-readable storage device.

It should be noted that in some embodiments, an apparatus used by optical data switching circuitry may include various components of the optical data switching circuitry **111** shown in FIG. **2** and/or the computing device shown in FIG. **1** and/or the example machine **300** shown in FIG. **3**. Accordingly, in some cases, techniques and operations described herein that refer to the optical data switching circuitry **111** may be applicable to an apparatus for optical data switching circuitry. In some embodiments, an apparatus for a computing device may include various components of the computing device **100** shown in FIG. **1** and/or optical data switching circuitry **111** shown in FIG. **2** and/or the example machine **300** shown in FIG. **3**. Accordingly, in some cases, techniques and operations described herein that refer to the computing device **100** may be applicable to an apparatus for a computing device.

In accordance with some embodiments, a processing element **113** of the optical data switching circuitry **111** may generate a plurality of optical data signals and may send the optical data signals to an optical switch **112** of the optical data switching circuitry **111**. The optical switch **112** may transmit the optical signals to a router **130** for relay to different destinations. The optical switch **112** may switch between transmission directions for transmission of the optical signals to different receiving ports of the router **130**. The receiving ports of the router **130** may be mapped to the different destinations, in some cases. These embodiments will be described in more detail below.

In accordance with some embodiments, a processing element **113** of the optical data switching circuitry **111** may generate a plurality of optical data signals and may send the optical data signals to an optical switch **112** of the optical data switching circuitry **111**. In some embodiments, the optical data switching circuitry **111** may include one or more of: a MEMS micro-mirror array **118**, and mirror control circuitry **119** to control the MEMS micro-mirror array **118**. In some embodiments, the MEMS micro-mirror array **118** and the mirror control circuitry **119** may be included in the optical switch **112**, although the scope of embodiments is not limited in this respect.

In some embodiments, the MEMS micro-mirror array **118** may reflect the optical signals (from the processing element **113**) to the router **130** for relay to different destinations. In some embodiments, the mirror control circuitry **119** may cause the MEMS micro-mirror array **118** to reflect the optical signals (from the processing element **113**) to the router **130** for relay to different destinations. In some embodiments, the mirror control circuitry **119** may control reflection, by the MEMS micro-mirror array **118**, of the optical signals (from the processing element **113**) to the router **130** for relay to different destinations.

In some embodiments, the MEMS micro-mirror array **118** may switch between reflection directions for reflection of the optical signals to different receiving ports of the router **130**. In some embodiments, the mirror control circuitry **119** may cause the MEMS micro-mirror array **118** to switch between reflection directions for reflection of the optical signals to different receiving ports of the router **130**. In some embodiments, the mirror control circuitry **119** may control switching, by the MEMS micro-mirror array **118**, between reflection directions for reflection of the optical signals to different receiving ports of the router **130**.

The receiving ports of the router **130** may be mapped to the different destinations, in some cases. These embodiments will be described in more detail below.

FIG. **4** illustrates the operation of a method of communication in accordance with some embodiments. In some embodiments, the method **400** may be performed by optical data switching circuitry such as **111**, although embodiments are not limited as such and the method **400** may be performed by other devices and/or components in some embodiments. In some embodiments, operations of the method **400** may be performed by components such as optical switches (such as **112**, **122**, **204** or other), MEMS micro-mirror arrays **118**, mirror control circuitry **119** and/or processing elements (such as **113-115**, **123-124**, **202** or other). Those components may be included in optical data switching circuitry (such as **111** or other) in some embodiments, although embodiments are not limited as such. In descriptions herein of techniques and/or operations, references may be made to components of either the first module **110** and/or second module **120**. Such references are not limiting, however, as the techniques and/or operations may be performed by other components (such as components shown in any of FIGS. **1-6**), in some embodiments. In addition, references may be made herein to the router **130**, but it is understood that these references are not limiting. Accordingly, some operations and/or techniques described herein may be performed using one or more routers in a different arrangement than the arrangement shown in FIG. **1**, in some embodiments.

It is important to note that embodiments of the method **400** may include additional or even fewer operations or processes in comparison to what is illustrated in FIG. **4**. In addition, embodiments of the method **400** are not necessarily limited to the chronological order that is shown in FIG. **4**. In describing the method **400**, reference may be made to FIGS. **1-3** and **5-6**, although it is understood that the method **400** may be practiced with any other suitable systems, interfaces and components.

It should also be noted that the method **400** may be applicable to an apparatus for optical data switching circuitry, an apparatus for an optical switch, an apparatus for a processing element, an apparatus for a router, an apparatus of a MEMS micro-mirror array, an apparatus of mirror control circuitry and/or an apparatus for another component, in some embodiments. In some embodiments, the modules **110**, **120** (and/or components of those modules) and the router **130** may operate as part of a system such as a computing device, computer, super-computer, exascale computer, switch, router, mobile device and/or other device. In some embodiments, the computing device **100** may be or may operate as part of a computer, super-computer, exascale computer, switch, router, mobile device and/or other device. Embodiments are not limited to these examples, however.

In some descriptions herein may refer to performance of one or more operations by the optical switch **112** and optical data switching circuitry **111**, but it is understood that one or more other components (including but not limited to the MEMS micro-mirror array **118**, mirror control circuitry **119** and other) may perform one or more of those operations, in some embodiments.

At operation **405** of the method **400**, a processing element **113** may generate one or more optical signals. At operation **410**, the optical switch **112** and mirror control circuitry **119** may determine reflection directions to be used for transmissions of optical signals, such as optical signals that may be received from the processing element **113** at operation **415**. In some embodiments, it may be necessary for operation **410** to be performed before operation **415**. The intended transmission direction(s) for the optical signals may need to be determined and/or known by the optical switch **112** and mirror control circuitry **119** before the optical signals arrive at the optical switch **112** and mirror control circuitry **119** due to the speed of light.

In some embodiments, the optical switch **112** and mirror control circuitry **119** may determine reflection directions to be used for reflection of the transmissions of the optical signals. For instance, locations of the router **130** may be mapped to different destinations. Accordingly, references herein to reflect in accordance with different directions are not limiting. The optical switch **112** may switch between reflection directions to reflect the optical signals to the different receiving ports of the router **130**, in some embodiments.

It should be noted that embodiments are not limited to usage of optical switches, as a MEMS micro-mirror array **118**, mirror control circuitry **119** and other components may be used in some embodiments. Accordingly, operations and/or techniques may be described herein with references to an optical switch (such as **112**, **122**, **204**), but it is understood that such references are not limiting, and the operations and/or techniques may also be performed using a MEMS micro-mirror array **118**, mirror control circuitry **119** and other components, in some embodiments.

In some embodiments, the optical signals may be sent by the processing element **113** to the optical switch **112** for relay to one or more destinations, such as other components that may or may not be included in the optical data switching circuitry **111**. As a non-limiting example, the destination may include another processing element **123** that may be included as part of a different optical data switching circuitry, in some cases. For instance, the processing element **113** that generates the optical signals may be part of the first module **110** (such as a processor board, circuit board or other) and the destination may be a processing element **123** that is part of a second module **120**.

It should be noted that embodiments are not limited to a single processing element **113**, as the optical switch **112** may receive one or more optical signals from multiple processing elements (such as **114**, **115** or other) included in the optical data switching circuitry **111**, in some embodiments. In addition, embodiments are also not limited to a single optical switch **112**, as the optical data switching circuitry **111** may include multiple optical switches **112**, in some embodiments.

FIG. **7** illustrates example flows of optical signals in accordance with some embodiments. It is understood that descriptions of FIG. **7** may refer to transmission of optical signals by the optical switch **112**, however, reflection of the optical signals (by the optical switch, MEMS micro-mirror array **118**, mirror control circuitry **119** and other component(s)) may be used instead of the transmission of the optical signals. The processing element **113** may generate a plurality of optical data signals (such as **712**, **722** and/or additional signals) and may send them to the optical switch **112** to be transmitted to the router **130** for relay to different destinations. As indicated by **710**, at a first time, a first optical data signal **712** may be sent to the optical switch **112** and may be transmitted by the optical switch **112** to the router **130** in accordance with a first transmission direction **714**. The router **130** may relay the first optical data signal **712** to a first destination, as indicated by **716**. As indicated by **720**, at a second time, a second optical data signal **722** may be sent to the optical switch **112** and may be transmitted by the optical switch **112** to the router **130** in accordance with a second transmission direction **724**. The router **130** may relay the second optical data signal **722** to a second destination, as indicated by **726**. This example may be extended to any suitable number of optical data signals, times, transmission directions, and destinations. In some embodiments, the optical switch **112** may switch between the transmission directions (**714**, **724** and/or others) for transmission of the optical data signals (**712**, **722** and/or others) to different receiving ports of the router **130**. The receiving ports of the router **130** may be mapped to different destinations, in some cases.

In some embodiments, one or more components, such as the MEMS micro-mirror array **118**, mirror control circuitry **119** and other, may perform operations that are the same as or similar to operations shown in FIGS. **5**-**7**. For instance, the MEMS micro-mirror array **118** may reflect optical signals in a manner that is similar to operations shown in FIGS. **5**-**7**, in some embodiments. In addition, the mirror control circuitry **119** may provide control functionality to enable the MEMS micro-mirror array **118** to reflect optical signals in a manner that is similar to operations shown in FIGS. **5**-**7**, in some embodiments.

In some embodiments, the optical signals may be based on one or more computed results, outputs or other information that are to be communicated to a destination. In some cases, the processing element **113** may perform one or more computations, may produce one or more outputs, may determine one or more values and/or may perform other operations to generate the optical signal. The optical signal may be based on such computations, outputs and/or values and may also include control information in some cases. The control information may be related to the destination of the optical signal, a route for the optical signal and/or other parameters related to the optical signal. Embodiments are not limited by these examples, however. In some cases, the processing element **113** may receive an optical signal from another component for forwarding and may or may not process the received optical signal before forwarding.

At operation **420** (FIG. **4**), the optical switch **112** and/or MEMS micro-mirror array **118** may reflect, in accordance with the reflection directions, the optical signals to the router **130**. The optical switch **112** and/or MEMS micro-mirror array **118** may switch between the reflection directions to reflect the optical signals at operation **425**. In some embodiments, the optical signals may be reflected to the router **130** for relay to one or more destinations. In some embodiments, the optical switch **112** and/or MEMS micro-mirror array **118** may switch between reflection directions to reflect the optical signals.

It should be noted that embodiments are not limited to usage of fiber optic routers. In some embodiments, a MEMS micro-mirror array **118**, mirror control circuitry **119**, another router and/or other component may be used as part of router **130**. As an example, a system of mirrors and/or a router that includes one or more mirror components may be used. In some embodiments, mirror control circuitry **119** may be used to provide control functionality to the system of mirrors. Accordingly, some operations and/or techniques may be described herein with references to a fiber optic router, but it is understood that such references are not limiting, and the operations and/or techniques may also be performed using other routers and/or components, in some embodiments.

In some embodiments, the reflection directions may be used to reflect the optical signals to different receiving ports of the router **130**. In some embodiments, reflection directions between the optical switch **112** (such as a transmitting port of the optical switch **112**) and corresponding receiving ports of the router **130** may be used by the optical switch **112** for directional reflection. The receiving ports may be mapped to the destinations of each optical signal, in some cases. Accordingly, reflection to a particular destination may be performed by using a directional reflection to a particular receiving port that is allocated for and/or mapped to communication between the optical switch **112** and the particular destination. Different receiving ports may be allocated for and/or mapped to communication between the optical switch **112** and different destinations. The optical switch **112** may communicate with the different destinations by reflecting to the corresponding receiving ports for those different destinations, in some cases. In some embodiments, an optical connection between the optical switch **112** and the particular receiving port may be used for the communication between the optical switch **112** and the particular destination. Multiple optical connections for the different destinations may enable the optical switch **112** to communicate with the different destinations, in some cases.

For reflection of multiple optical signals to multiple destinations, the optical switch **112** may switch between reflection directions, in some embodiments. Accordingly, the reflection directions may be switched in accordance with a relationship (such as a predetermined mapping or other mapping) between the receiving ports and the destinations. The reflection directions may be switched to enable the optical switch **112** to reflect to different receiving ports and/or to aim the reflection at the different receiving ports. As a non-limiting example, the reflections of the multiple optical signals to the multiple destinations may include sequential reflections performed in non-overlapping time periods, in some cases.

In some embodiments, the optical switch **112** may be optically coupled to the router **130**. As an example, a transmitting port of the optical switch **112** may be optically coupled to receiving ports of the router **130**. Accordingly, multiple optical connections (which may be represented by **118** in FIG. **1**) between the transmitting port of the optical switch **112** and the receiving ports of the router **130** may be used for communication. In addition, in some embodiments, a receiving port of the optical switch **112** may be optically coupled to transmitting ports of the router **130**, and optical connections between the receiving port of the optical switch **112** and the transmitting ports of the router **130** may be used for communication. The optical coupling may include free space optical coupling, in some embodiments.

In some embodiments, the optical switch **112** and/or MEMS micro-mirror array **118** may reflect and/or steer transmitted optical signals and/or beams between the receiving ports of the router **130**, in some embodiments. Accordingly, the optical switch **112** and/or MEMS micro-mirror array **118** may reflect and/or steer optical signals and/or beams between different optical connections between the optical switch **112** and the receiving ports of the router **130**, in some cases. In some embodiments, the optical switch **112** and/or MEMS micro-mirror array **118** may switch between the reflection directions for the reflection of the optical signals over different optical connections between the optical switch **112**/MEMS micro-mirror array **118** and different receiving ports of the router **130**, in some embodiments. The optical signals may be steered and/or transmitted over the optical connections in accordance with a free space optical coupling between the receiving ports and the optical switch **112**, in some embodiments.

The optical switch **112** may steer reflected optical signals and/or beams between the receiving ports, in some embodiments. The optical switch **112** may switch between the reflection directions for the reflection of the optical signals over different optical connections between the optical switch **112** and different receiving ports of the router **130**, in some embodiments. The optical signals may be transmitted over the optical connections in accordance with a free space optical coupling between the receiving ports and the optical switch **112**, in some embodiments.

In some embodiments, the receiving ports may be mapped to different destinations. Such a mapping may be a predetermined mapping or a mapping done at the router **130**, in some cases. As an example, a first receiving port of the router **130** may be used by the router **130** to receive a first optical signal from the optical switch **112** for relay to a first destination. The router **130** may route the received first optical signal to a particular transmitting port of the router **130** that is mapped as a transmitting port for transmission of optical signals to the first destination (or another optical switch that may relay the optical signals to the first destination). For instance, the first destination may be the processing element **123** of the second module **120**, and the router **130** may transmit the first optical signal to the optical switch **122** for relay to the processing element **123**.

Continuing the previous example, a second receiving port of the router **130** may be used in a similar manner by the router **130** to transmit optical signals from the optical switch **112** to a second destination (or to another optical switch for relay to the second destination). Additional receiving ports may be allocated in a similar manner to enable communication of optical signals from the optical switch **112** to any suitable number of destinations.

As another example, other receiving ports of the router **130** may be used in a similar manner to communicate optical signals from other optical signals to various destinations. As a non-limiting example, the router **130** may be configured to relay optical signals between any combination of four modules, A-D, each of which may comprise an optical switch and one or more processing elements. The first module A (which may be the first module **110** in FIG. **1**) may communicate optical signals to B, C or D. Accordingly, the router **130** may allocate a receiving port for communication from A to B (which may be the second module **120** in FIG. **1**), a receiving port for communication from A to C, and a receiving port for communication from A to D. Similarly, the router **130** may allocate a receiving port for communication from B to A, a receiving port for communication from B to C, and a receiving port for communication from B to D. Additional receiving ports may be allocated for communication from C to modules A, B, and D, and for communication from D to A, B, and C. The router **130** may allocate corresponding transmitting ports for each communication described above, and such routing may be performed internal to the router **130**, in some embodiments. It is understood that some descriptions may refer to transmission of optical signals by the optical switch **112**, however, reflection of the optical signals (by the optical switch, MEMS micro-mirror array **118**, mirror control circuitry **119** and other component(s)) may be used instead of the transmission of the optical signals.

In some embodiments, the optical switch **112** may be configured to transmit in accordance with a particular transmission direction based on one or more control signals applied to the optical switch **112**, the MEMS micro-mirror array **118** or the mirror control circuitry **119**. The control signals may, for example, comprise digital signals or analog signals (e.g., voltage levels). As an example, a control signal may indicate which transmission direction and/or which receiving port of the router **130** is to be used for a transmission of a particular optical signal. Accordingly, a switch in the control signal may indicate, to the optical switch **112**, to switch between transmission directions. The transmission directions may be mapped to the control signals in a predetermined manner, in some cases, although the scope of embodiments is not limited in this respect. It should also be noted that embodiments are not limited to usage of control signals, as the optical switch **112** may determine a transmission direction or may determine that the transmission direction is to be switched based on other factors. For instance, the optical switch **112** may use control information in the optical signals to make such a determination, in some embodiments.

In some embodiments, the optical switch **112** may switch transmission directions and/or steer transmissions of optical signals in accordance with a high-speed switching. A switching time for switching between two transmission directions, such as a maximum time, typical time and/or average time, may affect performance. In some embodiments, the transmission direction may be switched according to a particular increment, such as an increment of up/down angle, left/right angle and/or distance, within a particular time interval. The increment may be different for different combinations of first and second transmission directions, and a switching time may also vary accordingly. As an example, a first switching time may occur for a switch between transmission directions for two receiving ports located next to each other in a grid of the router **130**. A second switching time may occur for a switch between transmission directions for two receiving ports located at opposite ends of the grid. The first switching time may be lower than the second switching time, in some cases. As a non-limiting example, for high-speed switching, the first switching time may be less than one micro-second and the second switching time may be less than 20 micro-seconds. It should be noted that embodiments are not limited by these example numbers, as other suitable numbers may be used in some cases. It is understood that some descriptions may refer to transmission of optical signals by the optical switch **112**, however, reflection of the optical signals (by the optical switch, MEMS micro-mirror array **118**, mirror control circuitry **119** and/or other component(s)) may be used instead of the transmission of the optical signals.

It should be noted that in some embodiments, the optical switch **112** may transmit/reflect optical signals received from multiple processing elements (like **113-115** in the example of FIG. **1**) and/or receive optical signals intended for multiple processing elements (like **113-115**). For instance, the first module may include the optical switch **112** and multiple processing elements **113-115**. Accordingly, embodiments are not limited to usage of a single processing element **113**. Although some operations may be described herein in terms of one processing element **113**, it is understood that those operations and/or similar operations may be performed for multiple processing elements (like **113-115**).

As an example, the optical switch **112** may receive a first group of optical signals from a first processing element **113** and may transmit the first group of optical signals to the router **130** for relay to one or more destinations. The optical switch **112** may also receive a second group of optical signals from a second processing element **114** and may transmit the second group of optical signals to the router **130** for relay to one or more destinations. In some cases, the optical switch **112** may transmit optical signals in the first group and optical signals in the second group during a same time period and in a sequential manner, although the scope of embodiments is not limited in this respect. For instance, the optical switch **112** may transmit one or more optical signals from the first group, followed by one or more optical signals from the second group, followed by one or more additional optical signals from the first group. That is, the optical switch **112** may alternate between the two groups of optical signals. It should be noted that some embodiments and/or examples may be extended to more than two processing elements. It is understood that some descriptions may refer to transmission of optical signals by the optical switch **112**, however, reflection of the optical signals (by the optical switch, MEMS micro-mirror array **118**, mirror control circuitry **119** and/or other component(s)) may be used instead of the transmission of the optical signals.

Returning to the method **400** (FIG. **4**), the optical switch **112** may receive one or more inbound optical signals from the router **130** for relay to the processing element **113** at operation **430**. The optical switch **112** may send the optical signals to the processing element **113** at operation **435**. In some cases, the optical switch **112** may operate as a relay to communicate the inbound optical signals from one or more sources to the processing element **113**. The sources may include processing elements of other modules (such as processing elements **123-124** of the second module **120**) and/or one or more destinations from previously described operations. It should be noted that embodiments are not limited to usage of a single processing element **113**. In some embodiments, the optical switch **112** may receive inbound optical signals for multiple processing elements of the module (such as **113-115** of the first module **110**), may send those inbound optical signals to the multiple processing elements (such as **113-115**) and/or may operate as a relay for communication of inbound signals from one or more sources to multiple processing elements (such as **113-115**).

In some embodiments, the inbound optical signals may be or may include acknowledgement signals. As an example, an acknowledgement signal may indicate information about whether or not packets of a previously transmitted optical signal are successfully received by a destination. As another example, an acknowledgement signal may indicate information about the path between the optical switch **112** and the destination. For instance, the transmission direction used to transmit to the router **130** may be tuned, adjusted, optimized and/or improved by exchanging of signals between the optical switch **112** and the router **130**. In addition, a mapping between transmission directions and the receiving ports may be determined using such techniques. Other mappings, such as mappings between transmission directions and destinations, may also be determined using such techniques.

FIGS. **5** and **6** illustrate examples of optical connectivity between an optical switch and a router in accordance with some embodiments. It is understood that descriptions of FIGS. **5-6** may refer to transmission of optical signals by the optical switch **112**, however, reflection of the optical signals (by the optical switch, MEMS micro-mirror array **118**, mirror control circuitry **119** and other component(s)) may be used instead of the transmission of the optical signals.

It should be noted that embodiments are not limited to the examples of connectivity **500** or **600** shown in FIGS. **5** and **6**, in terms of number, type and/or arrangement of components. As an example, four modules **530**, **540**, **550**, and **560** (denoted as A-D) may be arranged in stack configuration and may communicate with each other through the router **510**. Embodiments are not limited to the stack configuration and are also not limited to four modules. In the example connectivity shown in FIG. **5**, a top view **515**, side view **520**, and end view **525** are shown. In some embodiments, the modules may be arranged in a stack arrangement adjacent to the router with reflective and/or transmissive optical elements that provide optical transmission paths between the optical switches and the receiving ports of the router. In some embodiments, the modules may be arranged in stacks, layers or a combination of stacks and layers adjacent or surrounding the router. In these embodiments, reflective and/or transmissive optical elements may provide optical transmission paths between the optical switches and/or the MEMS micro-mirror arrays and the receiving ports.

The module **530** may include an optical switch **535**. In some cases, the optical switch **535** may include one or more transmission ports **536** and one or more receiving ports **537**. The top view **515** and side view **520** show communication (denoted by **538**) between the optical switch **535** and the router **510**. The other modules **540**, **550**, **560** may also include an optical switch (shown as **545**, **555**, and **565**) and may communicate with the router as denoted by **548**, **558**, and **568**. Routing of the signals between the receiving ports **570** of the router and the transmitting ports **575** of the router are shown in the end view **525**.

FIG. **6** illustrates another example of optical connectivity between an optical switch and a router in accordance with some embodiments. The transmit/receive (T/R) module **610** (labeled as A) and the modules **620-640** (labeled as B, C, and D) may be arranged in a stack configuration and connected to a router **650**. As shown in the bottom portion of FIG. **6**, the router may route received signals from modules **610**, **620**, and **630** (shown as **651**, **652**, and **653**) to a transmitting port **654** for transmission to module **640**. Similar connectivity for transmission to the other modules **610**, **620**, and **630** may also be implemented, in some cases.

In some embodiments, free space optical data coupling from each of multiple processor boards to a router may be utilized. There may be one transmitter/receiver (T/R) module for each processor board, in some cases. In some embodiments, optical data from the transmitter module may be switched by an optical switch. As an example, a MEMS micro-mirror array may be used in some cases. These examples are not limiting, as other types of optical switches are possible in some cases. The optical switch may steer the transmitter laser beam to the port for the desired processor board receiver. There may be one receiver for each processor board that may receive, from the router, data from other boards. Referring to the end view **525** of FIG. **5** as an example, fiber optic cables from processor boards A, B and C may be combined (for example, by splicing) in the router **510** to route the data to the receiver for processor board D. Similar fiber optic cabling for the data going to each of the other processor boards in the stack may be used.

In some embodiments, high-speed switching may be performed by the optical switch comprising a MEMS micro-mirror array. As an example, the optical switch may switch from one spot to another in a few microseconds, and a maximum time may be about 20 microseconds. In some embodiments, scalability may be realized. As an example, the optical switch may steer the laser beams to **400** spots, in some cases. In some cases, the optical switch may utilize a relatively low power consumption and may require little cooling.

In some embodiments, free space optical coupling between the router and the boards may be used. Accordingly, the optical connections may be made without a need for access to the back side of the board, in some cases. In some cases, optical data may be switched between many processors. In some cases, an order of magnitude more processors may be connected for parallel processing in comparison to other devices. In some cases, high-speed data optical switching may be realized. In some cases, techniques described herein may be used as part of "big data" processing systems and/or data centers.

It should be noted that one or more devices and/or embodiments descried herein may include one or more of: a MEMS micro-mirror array, circuitry related to MEMS, one or more mirrors, one or more mirrors configured to perform one or more operations such as reflection, mirror control circuitry, control circuitry that is configured to perform at least one control for a component (such as the MEMS micro-mirror array, circuitry related to MEMS, one or more mirrors, one or more mirrors configured to perform reflection and/or other operations, and/or other component(s)), and/or other.

In addition, one or more devices and/or embodiments described herein may be related to: usage of a MEMS micro-mirror array capable of digitally controlling light; control circuitry for controlling the array; means for controlling the array; a digitally controlled MEMS array; and/or similar.

In addition, one or more devices and/or embodiments described herein may be related to the following. In some cases, the MEMS micro-mirror array may enable a much wider range of wavelengths compared to a waveguide, liquid crystal waveguide (LCWG) because only the coatings may need to be changed, not the entire material system. Emerging MEMS micro-mirror arrays also nearly completely fill the aperture and have both tilt and piston control. Completely filling the aperture increases the sensor throughput. The piston control adds the capability to correct the wavefront to mitigate the effects of atmospheric absorption, scatter and thermal blooming and optical distortion that degrade the sensor performance.

It should be noted that some descriptions herein may refer to performance of one or more operations by a component such as an optical switch, optical data switching circuitry, and/or other component. It is understood that one or more other components (including but not limited to a MEMS micro-mirror array, mirror control circuitry and/or other) may perform one or more of those operations, in some embodiments.

In some embodiments, a MEMS micro-mirror array may reflect optical signals. In some embodiments, mirror control circuitry may provide control functionality for the MEMS micro-mirror array to reflect the optical signals. It is understood that in some embodiments, a MEMS micro-mirror array may perform one or more of the same operations and/or similar operations, wherein the MEMS micro-mirror array reflects optical signals. The mirror control circuitry may perform control functionality for one or more of those operations, although the scope of embodiments is not limited in this respect.

In some embodiments described herein, operations related to "steering of optical signals" or "transmission of optical signals" or similar may be related to "reflection of optical signals by a MEMS micro-mirror array". For instance, in some embodiments, reflection by the MEMS micro-mirror array may replace steering by a LCWG in one or more of the described embodiments.

While several illustrative embodiments of the invention have been shown and described, numerous variations and alternate embodiments will occur to those skilled in the art. Such variations and alternate embodiments are contemplated and can be made without departing from the spirit and scope of the invention as defined herein.

The Abstract is provided to comply with 37 C.F.R. Section 1.72(b) requiring an abstract that will allow the reader to ascertain the nature and gist of the technical disclosure. It is submitted with the understanding that it will not be used to limit or interpret the scope or meaning of the claims. The following claims are hereby incorporated into the detailed description, with each claim standing on its own as a separate embodiment.

The invention claimed is:

1. Optical data switching circuitry, comprising:
- a processing element, configured to generate a plurality of optical signals; and
- an optical switch comprising a micro-electronic mechanical system (MEMS) micro-mirror array, configured to:
- reflect the optical signals to a router for relay to different destinations; and
- switch between reflection locations for reflection of the optical signals over different optical connections for the destinations, the optical connections between the optical switch and different receiving ports of the router,
- wherein the optical signals are sequentially switched between different transmission directions to the different receiving ports of the router in non-overlapping time periods in accordance with a predetermined mapping between the transmission directions and the receiving ports.

2. The optical data switching circuitry according to claim **1**, wherein the reflection locations are switched in accordance with a high-speed switching for which a switching time is 20 micro-seconds or less.

3. The optical data switching circuitry according to claim **1**, wherein the optical signals are reflected over the optical connections in accordance with a free space optical coupling between the receiving ports and the optical switch.

4. The optical data switching circuitry according to claim **1**, wherein the optical switch is further configured to switch between the reflection locations based on a predetermined mapping between the reflection locations and a control voltage and/or control signals applied to the optical switch.

5. The optical data switching circuitry according to claim **1**, wherein the optical switch is further configured to switch between the reflection locations based on destination indicators included in data packets of the optical data signals.

6. The optical data switching circuitry according to claim 1, wherein the router comprises: a second MEMS micro-mirror array; and mirror control circuitry to control the second MEMS micro-mirror array.

7. The optical data switching circuitry according to claim 1, wherein the router is a fiber optic router.

8. The optical data switching circuitry according to claim 1, wherein:

the plurality of optical signals is a first plurality of optical signals,

the optical data switching circuitry further comprises one or more other processing elements, and

the optical switch is further configured to:

reflect a second plurality of optical signals from the other processing elements to the router for relay to the destinations; and

switch between the reflection locations for the reflection of the second plurality of optical signals over the optical connections.

9. The optical data switching circuitry according to claim 1, the optical switch further configured to:

receive a plurality of inbound optical signals from the router for elay to the processing element; and

switch between receive directions for the reception of the inbound optical signals over different inbound optical connections between the optical switch and different transmitting ports of the router,

wherein the receive directions are switched in accordance with a predetermined mapping between the transmitting ports and a group of sources of the inbound optical signals, and

wherein the inbound optical signals are received over the inbound optical connections in accordance with a free space optical coupling between the transmitting ports and the optical switch.

10. The optical data switching circuitry according to claim 9, wherein the received inbound optical signals include an acknowledgement signal from one of the destinations, the acknowledgement signal based on a reception of one of the optical signals at the destination.

11. Optical data switching circuitry, comprising:

a processing element, configured to generate a plurality of optical signals; and

an optical switch comprising a micro-electronic mechanical system (MEMS) micro-mirror array, configured to:

reflect the optical signals to a router for relay to different destinations; and

switch between reflection locations for reflection of the optical signals over different optical connections for the destinations, the optical connections between the optical switch and different receiving ports of the router,

wherein the reflection locations are switched in accordance with a predetermined mapping between the receiving ports and the destinations,

wherein:

the plurality of optical signals is a first plurality of optical signals,

the optical data switching circuitry further comprises one or more other processing elements, and

the optical switch is further configured to:

reflect a second plurality of optical signals from the other processing elements to the router for relay to the destinations; and

switch between the reflection locations for the reflection of the second plurality of optical signals over the optical connections, and

wherein the optical switch is configured to reflect at least a portion of the first plurality of optical signals and at least a portion of the second plurality of optical signals sequentially and during a same time period.

12. Optical data switching circuitry, comprising:

a processing element, configured to generate a plurality of optical data signals;

a micro-electronic mechanical system (MEMS) micro-mirror array, configured to reflect the optical data signals to different receiving ports of a router for relay to different destinations,

wherein the optical signals are sequentially switched between different transmission directions to the different receiving ports of the router in non-overlapping time periods in accordance with a predetermined mapping between the transmission directions and the receiving ports.

13. The optical data switching circuitry according to claim 12, wherein the MEMS micro-mirror array is further configured to receive the optical data signals from the processing element.

14. The optical data switching circuitry according to claim 12, wherein the MEMS micro-mirror array is further configured to reflect the optical data signals to the receiving ports of the router in accordance with different directions between the MEMS micro-mirror array and the receiving ports.

15. The optical data switching circuitry according to claim 14, wherein the MEMS micro-mirror array is further configured to reflect the optical data signals in accordance with a predetermined mapping between the directions and one or more control voltages applied to the optical switch.

16. The optical data switching circuitry according to claim 12, wherein:

the processing element is a first processing element and the plurality of optical data signals is a first plurality of optical data signals,

the MEMS micro-mirror array is further configured to reflect a second plurality of optical data signals from a second processing element of the optical data switching circuitry to the router for relay to the destinations, and

the reflections of the second optical data signals are steered between the receiving ports in accordance with the predetermined mapping between the receiving ports and the destinations.

17. The optical data switching circuitry according to claim 12, wherein the MEMS micro-mirror array is configured to operate as a relay by receiving incoming optical data signals intended for the processing element from the router, and by reflecting the incoming optical data signals to the processing element.

18. The optical data switching circuitry according to claim 12, wherein the router comprises one or more MEMS micro-mirror arrays.

19. The optical data switching circuitry according to claim 12, wherein the router is a fiber optic router.

20. An optical data communication apparatus, the apparatus comprising:

optical switches; and

a router, configured to operate as a relay to exchange optical data signals between the optical switches,

wherein the optical switches are configured to switch between reflection directions to reflect the optical signals over different optical connections between the optical switches and different receiving ports of the router, wherein the router includes a micro-electronic mechanical system (MEMS) micro-mirror array configured to reflect received optical signals to the destinations; and

wherein the optical signals are sequentially switched between different transmission directions to the different receiving ports of the router in non-overlapping time periods in accordance with a predetermined mapping between the transmission directions and the different receiving ports.

21. The communication apparatus according to claim **20**, wherein the MEMS micro-mirror array comprises a system of mirror elements configured to reflect the received optical signals to the destinations.

22. The communication apparatus according to claim **20**, wherein the reflection directions are switched in accordance with a high-speed switching for which a switching time is 20 micro-seconds or less.

23. The communication apparatus according to claim **20**, wherein the optical signals are reflected over the optical connections in accordance with a free space optical coupling between the receiving ports and the optical switch.

24. The communication apparatus according to claim **20**, wherein the optical switches are further configured to switch between the reflection directions based on predetermined mappings between the reflection directions and control voltages applied to the optical switches.

25. The communication apparatus according to claim **20**, wherein:

the communication apparatus comprises multiple modules, and

each of the modules comprises one of the optical switches and a group of one or more processing elements to generate the optical signals.

26. The communication apparatus according to claim **25**, wherein the modules are arranged in a stack arrangement adjacent to the router with reflective and/or transmissive optical elements that provide optical transmission paths between the optical switches and the receiving ports of the router.

27. The communication apparatus according to claim **20**, wherein the optical switches include one or more MEMS micro-mirror arrays and/or mirror control circuitry to provide control functionality for the one or more MEMS micro-mirror arrays.

28. The communication apparatus according to claim **20**, wherein the communication apparatus is an exascale computing device.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 11,042,025 B2
APPLICATION NO. : 16/871602
DATED : June 22, 2021
INVENTOR(S) : Uyeno et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the Specification

Column 2, Line 19, delete "110." and insert --120.-- therefor

Column 4, Line 47, delete "(USB)," and insert --(USB)),-- therefor

Column 15, Line 31, delete "descried" and insert --described-- therefor

In the Claims

Column 17, Line 24, Claim 9, delete "elay" and insert --relay-- therefor

Column 18, Line 62, Claim 20, before "signals", delete "data"

Signed and Sealed this
Fourteenth Day of September, 2021

Drew Hirshfeld
Performing the Functions and Duties of the
Under Secretary of Commerce for Intellectual Property and
Director of the United States Patent and Trademark Office